NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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VISIBILITY OF VARIOUS TARGET-BACKGROUND COLOR COMBINATIONS UNDER DIFFERENT CHROMATIC AMBIENT ILLUMINATIONS

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Naval Medical Research and Development Command
Research Work Unit M0100.001-1019

Released by:

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Commanding Officer
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SUMMARY PAGE

THE PROBLEM

To determine the most visible combinations of target and background colors viewed on CRTs under the various colors of ambient illumination found on submarines.

FINDINGS

Opponent colors are most quickly detectable. Luminance contrast is more effective in increasing visibility of a target than is color contrast. Dim chromatic ambient light does not affect the visibility of bright targets on the CRT screen.

APPLICATION

These findings indicate which colors should be used in adding color coding to submarine CRT displays, and that the effectiveness of color coding will not be affected by the dim colored overhead lights currently in use on submarines.

ADMINISTRATIVE INFORMATION

This research was conducted as part of the Naval Medical Research and Development Command Work Unit M0100.001-1019 - "Improvement of sonar performance through modification of sonar displays." It was submitted for review on 27 Jul 1984, approved for publication on 24 Aug 1984, and designated as NSMRL Report No. 1027.

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ABSTRACT

The detectability of seven colors presented on a CRT against four background colors was measured under four conditions of ambient lighting. Opponent color pairs were most quickly detected. Detection was enhanced by maximizing both luminance and color contrast, but luminance contrast was much more effective. Chromatic ambient lighting which was a log unit dimmer than the target luminance had no effect on performance.

INTRODUCTION

Traditionally, CRTs in the sonar control rooms of submarines have been monochromatic. However, owing to advances in technology and reductions in cost, color CRTs are now being planned for some of the new sonar systems. In deciding to use color coding, a number of factors must be taken into consideration: the operator's task, the type of display, the form of the data, the number of colors, the actual colors to be used, the luminance of the displays, and the luminance and color of the ambient lighting.

Much of the previous experimentation has been performed on data which are highly processed before being presented to the operator in the form of graphics or, more frequently, alphanumerics. In contrast, much of the data presented to a sonar operator is in more of a "raw" form; the operator is attempting to detect a target line somewhere in a "waterfall" display. If color is to be considered for such displays, then the first question is which color combinations would be most distinguishable. In other words, which color combinations provide the greatest contrast and so are the most likely to enhance detection? Opponent color theory (1) leads one to predict that the two opponent color pairs, around which the visual system appears organized, would offer the most contrast. These pairs are red-green and yellow-blue.

A second question is whether or not a given color is best for the CRT background, if the system is limited to a single one. Currently the background is black. If the raw data were to be color coded, perhaps a certain background color would offer the greatest contrast with a wide variety of target colors, resulting in enhanced detection.

Finally, it is of practical importance to investigate performance under different colors of ambient illumination, since a variety of colors is now being used to illuminate submarine compartments. Blue is most common in sonar control rooms, red is still used in the control area, but subdued white is now being recommended for future use in sonar and control (2). At times sonarmen prefer to operate with no lights on at all. What is the effect of the use and color of ambient illumination on the visibility of chromatic CRT displays?

This study addressed these three questions. We tested the visibility of seven target colors on four colored backgrounds under three colors of ambient illumination and in the dark. Our purpose was to reveal the effects of illumination color and various color pairings on a simple detection task performed on a color CRT.

EXPERIMENT I
Method

Subjects

Six male and two female members of the Naval Submarine Medical Research Laboratory staff served as subjects. All had normal color vision and either had, or were corrected to, normal visual acuity. All had considerable experience as observers in psychophysical experiments.

Lighting Conditions

The conditions of ambient illumination were red, blue, subdued white, and no light ("none"). The three lighted conditions were matched for .2 footcandles (fc) of photopic illumination falling on the CRT screen, as measured by a Gossen footcandle meter, the general procedure that would be followed on submarines. This value was chosen because it falls within the range of values measured aboard submarines (3). Illumination, when present, was provided by two cool-white fluorescent bulbs in a fixture mounted approximately one meter above and one meter behind the seated subject. The red and blue conditions were produced by covering the bulbs with red or blue plastic sleeves, with transmittances of .019 and .023, respectively. These sleeves are identical to those used on submarines to provide colored lighting and are available from the GSA catalog. Sleeves of neutral-density filter material produced the subdued white condition. The bulbs were turned off in the no light condition. The chromaticities of the bulbs covered by the red, blue, and neutral sleeves are shown in Fig. 1 and listed in Table I.

Stimuli

The target stimuli were colored circles, 18' visual angle in diameter. Six colors, in addition to gray, were chosen to sample the range of the visible spectrum: purple, blue, green, yellow, orange, and red. The chromaticities of the three phosphors and the seven stimuli are shown in Fig. 1 and listed in Table I. They were presented on an Advanced Electronics Design model 512 color graphics terminal under the control of a PDP 11/04 laboratory computer. The spectral emission curves of the red, green, and blue phosphors were measured, and, with additional calibrations, the chromaticities of any colored stimuli could be computed. Maximum saturation for any color resulting from the mixture of the three phosphor primaries is represented by the lines of the triangle connecting the coordinates of the primaries in Fig. 1. The stimulus colors were made as saturated as possible, as shown by their proximity to the lines of this triangle.

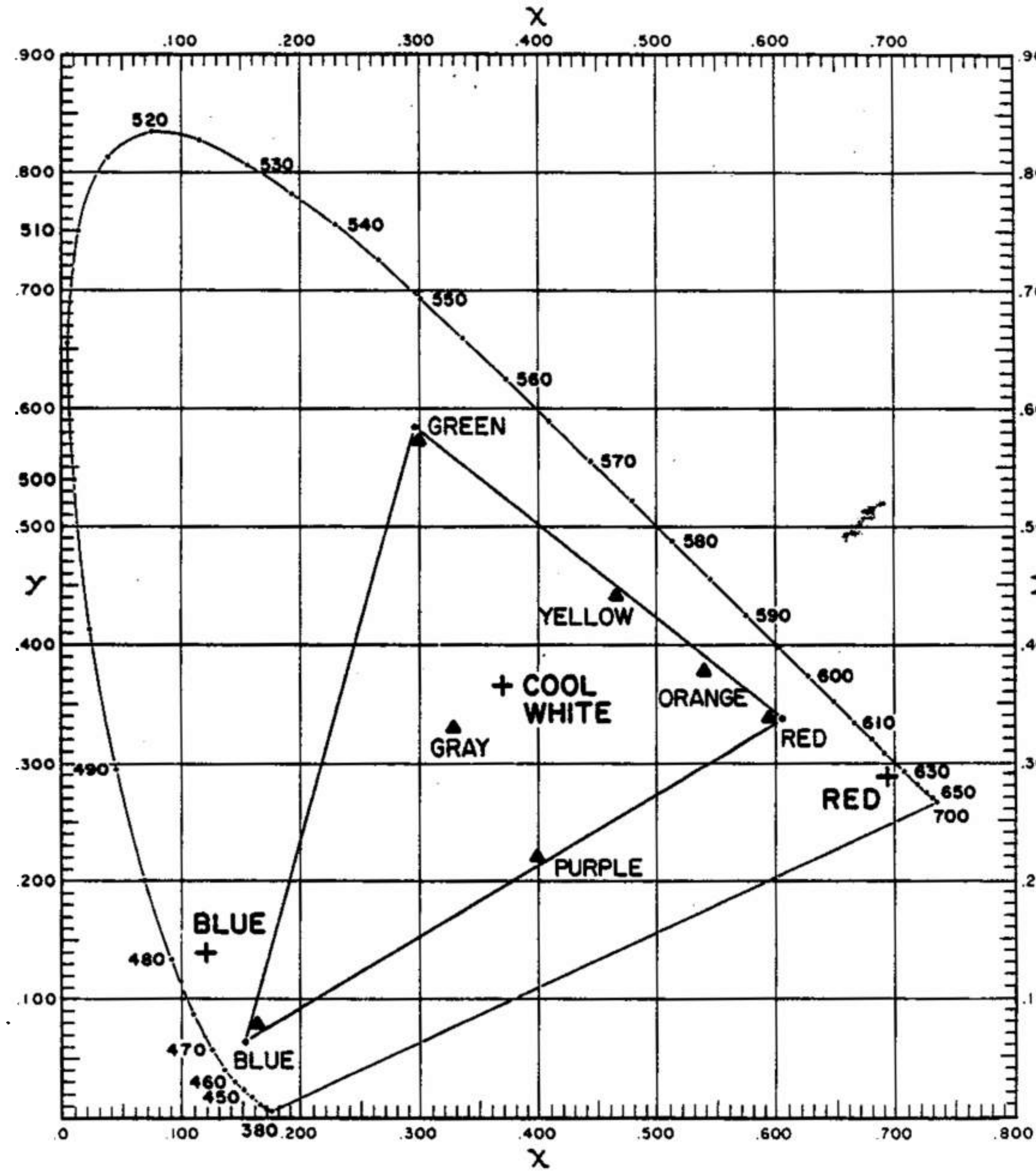

FIGURE 1. The chromaticities of the cool-white bulbs and the bulbs covered by the colored filters are represented by +. The chromaticities of the three CRT phosphors are the points of the triangle. All realizable colors fall within this triangle. The stimulus chromaticities are represented by ▲.

TABLE I. The chromaticity coordinates and abbreviations for the illumination conditions, CRT phosphors, and colored stimuli used in this experiment.

ILLUMINATION CONDITIONS	x	y
RED (R)	.70	.29
BLUE (B)	.12	.14
WHITE (W)	.37	.37
NONE (N)	--	--
PHOSPHORS		
RED	.60	.34
GREEN	.30	.58
BLUE	.15	.07
STIMULI		
RED (R)	.60	.34
ORANGE (O)	.54	.38
YELLOW (Y)	.47	.44
GREEN (G)	.30	.57
BLUE (B)	.16	.08
PURPLE (P)	.40	.22
GRAY (GY)	.33	.33

Four of these colors (red, yellow, green, and blue) were used as background colors covering the entire CRT screen; on each background, the other six were used as targets.

The luminances of all stimuli were matched photopically at 4 footlamberts (fL) by means of a Spectra Pritchard model 1970 photometer. The colors were equated at photopic levels rather than at the mesopic viewing levels of the experiment, the procedure that is typically used on submarines. However, stimuli matched in luminance do not necessarily appear equally bright (4,5), and, in fact, the blue was brighter than the other six colors. Under photopic conditions this difference was about 0.1 log unit, but it reached almost 1 log unit at the mesopic level. The major reasons for this are well known (6). First, photometers underestimate the brightness of short wavelengths, particularly when the viewing field is large, as it was in this experiment. Second, the eye becomes relatively more sensitive to these shorter wavelengths as the overall level of illumination decreases.

Procedure

The experimental design was a four-alternative forced choice procedure. A target appeared in the center of one of the quadrants of the screen, and the subjects' task was to decide as quickly as possible in which quadrant the target was being presented. Subjects were seated 30 inches from the CRT screen, which was 15 x 21 degrees visual angle and placed at eye level. The background color filled the screen and was present for the entire session. A warning tone sounded, followed after a 1.5 sec delay by the target. The target color replaced, rather than mixed with, the background color. The subject held in his lap a small response panel with four buttons, one for each quadrant. The target remained on until a button was pushed. The computer then recorded the correctness of the answer and the reaction time. There was a 2.5 sec delay before the start of the next trial. The color of the target and its location on each trial were randomized separately for each session. Each target color appeared in each of the four possible locations five times, for a total of 120 target presentations per session. One of the four background colors under one of the four illumination conditions was tested in each session. Every subject performed under every condition. The order of presentation of lighting conditions and background colors was counterbalanced across subjects. The experiment, therefore, required 16 sessions per subject for completion. Subjects participated for eight days, completing two of the 20 minute sessions each day, with a five minute break in between.

Results

There are three variables of interest in this experiment: ambient illumination, CRT background color, and target color. The statistical analysis of the effects of ambient illumination and background color was performed separately from that of target color. There were two reasons for this. First, not all target colors were used with all background colors, which prevented the use of an analysis of variance that included all variables. Like color pairs were omitted because it is impossible to detect a target against an identical background. Different shades of the same colors were not used because such combinations would never be considered feasible in practical applications. Second, this method enabled us to analyze target color separately for each background color, and so discover those color combinations resulting in the fastest reaction times.

Ambient Illumination

The mean reaction times (RTs), collapsed across all target and background colors, are shown in Fig. 2 for the four ambient illuminations. There is very little difference in the RTs to the four ambient colors, and none of the differences was significant, according to a two-way, repeated measures analysis of variance (illumination x background color x subject). Therefore, the data collected under the four ambient illuminations were combined in all subsequent analyses.

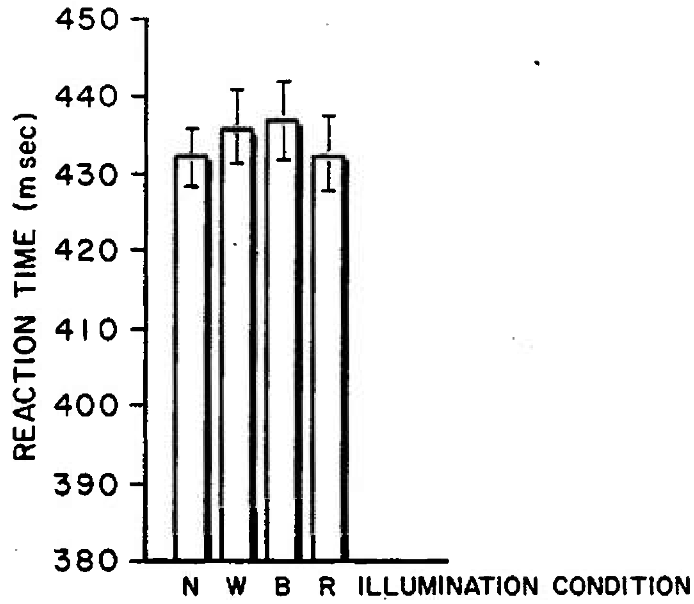

FIGURE 2. Mean reaction times for the four illumination conditions in Expt. I collapsed across target color and background color. See Table I for abbreviations. Error bars represent ± 1 s.e.m.

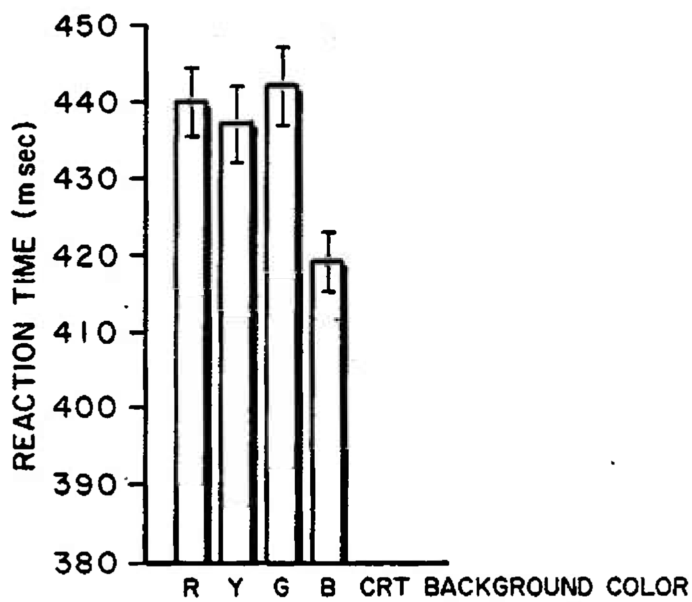

FIGURE 3. Mean reaction times for the four background colors in Expt I collapsed across target color and illumination condition. SeeTable I for abbreviations. Error bars represent ± 1 s.e.m.

CRT Background Color

The mean RTs for the four background colors, collapsed across all target colors and ambient illuminations, are shown in Fig. 3. The same analysis of variance described above showed the effect of background color to be significant ($F(3,21) = 4.6$, $p < .05$). The Newman-Keuls post hoc test showed that the mean RT with blue was significantly faster than with the green background ($p < .05$), and approached significance compared to the red. Furthermore, the blue background was equally advantageous under all four ambient illuminations, since the interaction between background color and ambient illumination was not significant. This consistent advantage for blue under all illumination conditions is clearly illustrated in Fig. 4. The average RTs are lowest with the blue background under all four ambient illuminations; every one of the average RTs for the 12 other background color/ambient illumination combinations is longer than any of the RTs with the blue background. It is clear that the blue background used in this experiment offered a consistent and sizeable advantage over the other background colors.

Target Color

As mentioned above, the effect of target color was analyzed separately on each of the backgrounds, because not all target colors appeared on all backgrounds. Fig. 5 shows the mean RTs to the various target colors on each of the background colors. There was much more variability in the RTs for the different target colors on the red, yellow, and green backgrounds than for targets on the blue background. No mean RT exceeded 430 msec on the blue background. On each of the other background colors, mean RTs to at least three of its six targets exceeded 430 msec. The significance of these differences was determined with a one-way, repeated measures analysis of variance (target color x subject) for each of the background colors. RT differences between target colors were significant for the blue background ($F(5,35) = 2.82$, $p < .05$) and highly significant for the red ($F(5,35) = 11.74$, $p < .01$), yellow ($F(5,35) = 18.30$, $p < .01$), and green ($F(5,35) = 45.58$, $p < .01$) backgrounds.

The Newman-Keuls test was used to determine which RT differences between target colors were significant for each of the background colors. Table II shows the results. There are clearly different patterns of results for target detection against the different backgrounds. Fig. 6 shows the stimulus colors arranged as a wheel; it is of help in uncovering a pattern in these results. Generally, the more similar the target color is to the background (the closer they are on the color-wheel), the longer the RTs. The more contrast the two colors have (the farther apart they are on the wheel), the shorter the RTs. This pertains to colored targets, not the gray. For example, on the red background, green and blue were the colors with the fastest response times, while purple, orange, and yellow produced the slowest RTs. On the yellow background, blue, red, and purple targets produced the fastest

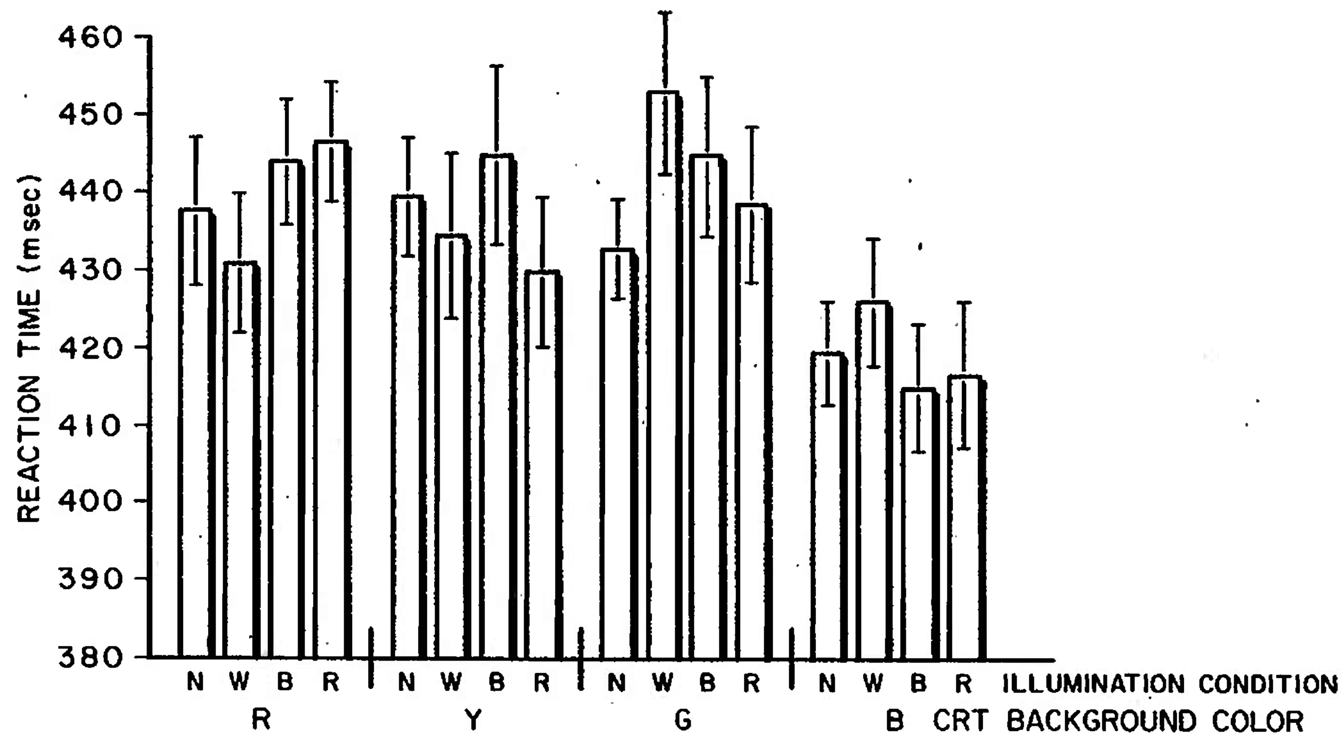

FIGURE 4. Mean reaction times for illumination condition/background color combinations in Expt. I, collapsed across target color. See Table I for abbreviations. Error bars represent ± 1 s.e.m.

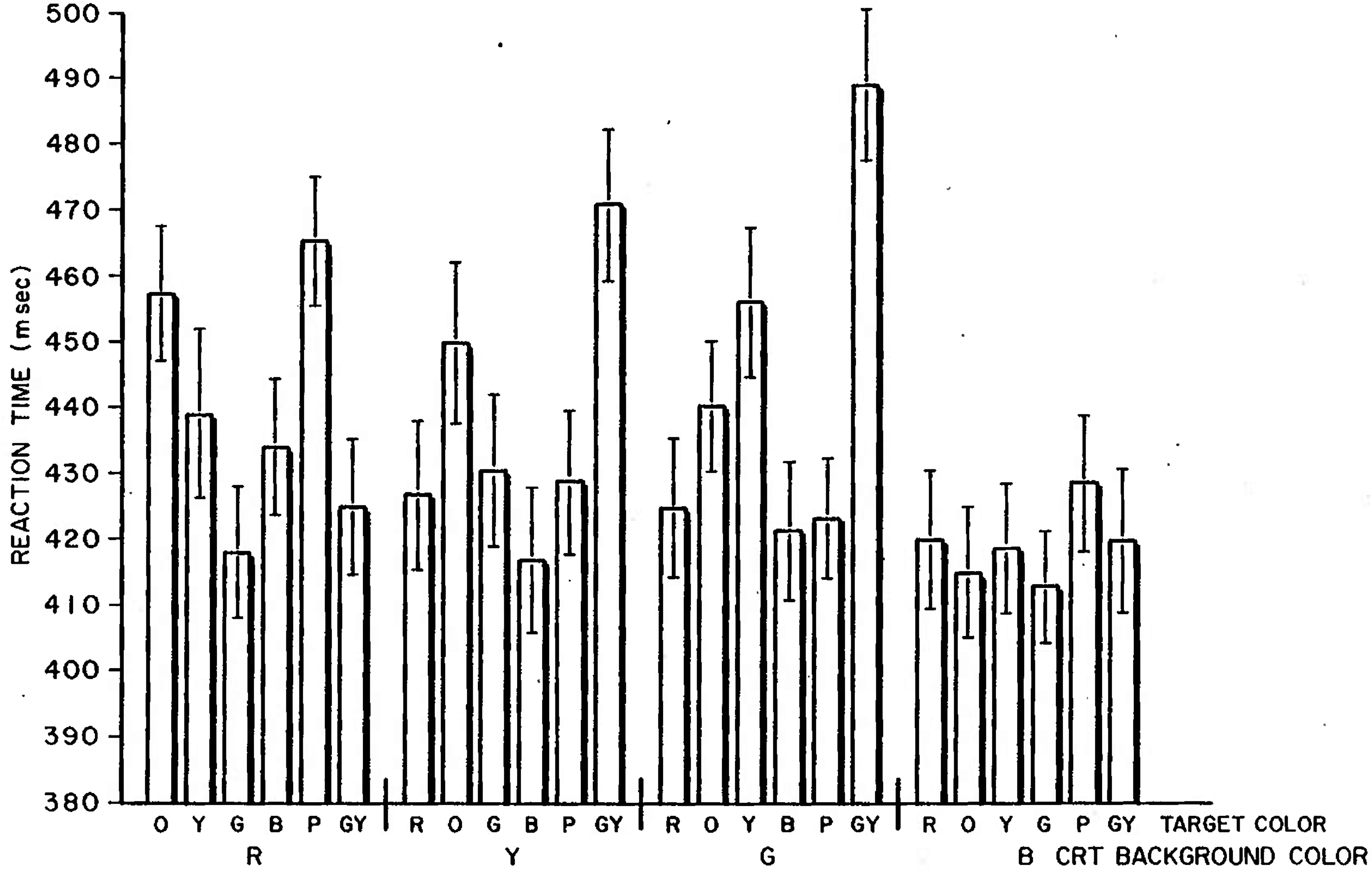

FIGURE 5. Mean reaction times for the various target colors on the four backgrounds in Expt. I, collapsed across illumination condition. See Table I for abbreviations. Error bars represent ± 1 s.e.m.

TABLE II. Results of Newman-Keuls test for differences in mean reaction time (msec) between target colors on the various backgrounds. Targets are ordered from fastest to slowest reading left to right or top to bottom.

RED BACKGROUND

	GREEN	GRAY	BLUE	YELLOW	ORANGE	PURPLE
GREEN		6.8	15.9	21.0	39.4**	47.5**
GRAY			9.1	14.2	32.6	40.7**
BLUE				5.1	23.5	31.6**
YELLOW					18.4	26.5
ORANGE						8.1

YELLOW BACKGROUND

	BLUE	RED	PURPLE	GREEN	ORANGE	GRAY
BLUE		10.0	11.8**	13.4*	33.1*	54.1**
RED			1.8	3.4	23.1**	44.1**
PURPLE				1.6	21.3	42.2**
GREEN					19.7	40.7**
ORANGE						21.0

GREEN BACKGROUND

	BLUE	PURPLE	RED	ORANGE	YELLOW	GRAY
BLUE		1.6	3.2	18.9**	34.6**	67.4**
PURPLE			1.6	17.2*	33.0**	65.8**
RED				15.7**	31.4**	64.2**
ORANGE					15.7*	48.5**
YELLOW						32.8**

BLUE BACKGROUND

	GREEN	ORANGE	YELLOW	GRAY	RED	PURPLE
GREEN		1.7	5.4	6.8	7.1	15.6
ORANGE			3.7	5.1	5.4	13.9
YELLOW				1.4	1.7	10.2
GRAY					0.3	8.8
RED						8.5

* $p < .05$;
** $p < .01$

RTs, orange and green the slowest. This trend is not as strong for the green background where blue, purple, and red were the fastest, with yellow and orange the slowest. The blue background produced smaller differences among target colors, as mentioned above, yet the pattern is consistent with that for the other backgrounds.

An additional finding is worth mentioning. There is an interesting variability associated with the gray targets. There were very high RTs for the gray targets on the yellow and green backgrounds and very low RTs on the red and blue backgrounds.

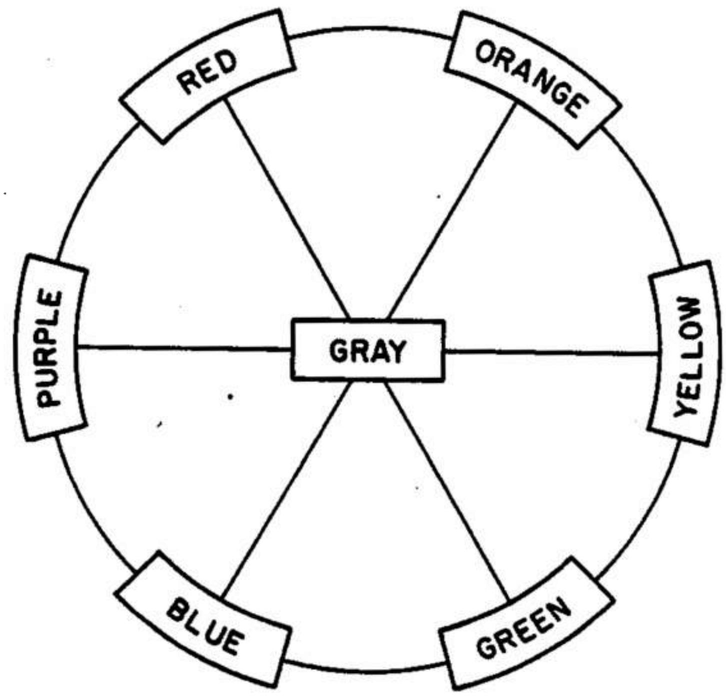

FIGURE 6. The target and background colors used in these experiments, arranged on a color-wheel, following the color spectrum.

EXPERIMENT II

Since the blue was appreciably brighter than the other colors under the mesopic viewing conditions, it was not clear whether the apparent advantage of the blue background was due to its hue or its brightness. The experiment was therefore repeated with the blue matched in brightness to the other colors by four experienced observers.

Method

Subjects

Eight male students at the Naval Submarine School served as subjects. All had normal color vision and were corrected to normal visual acuity. None had any experience as an observer in such experiments.

Lighting conditions

Since the different colors of ambient illumination had no effect on the results in Expt. I, only subdued white was used as the ambient illumination in this experiment.

Stimuli

Three colored backgrounds were used, blue, green, and yellow, matched for brightness under the mesopic viewing conditions by four experienced observers using the method of adjustment. The red background was omitted because it was not significantly different from the yellow and green backgrounds which bracketted the red for mean RT (Fig.3). In addition, a black background was tested.

The six target colors other than the background color were again presented against each background. On the black background, the target colors were red, orange, green, blue, purple, and gray. The chromaticities of all these colors were the same as in Expt. I. Yellow was omitted because only six target colors could be chosen for the black background and yellow fell in the middle of the group for mean RT in Expt. I.

Procedure

The procedure was identical to that used in Expt. I, except that the subjects completed the four sessions (one session for each of the four backgrounds) in one afternoon. Presentation of the background conditions was randomized separately for each subject.

Results

Background color

Figure 7 shows that with the brightnesses of the colors matched, the blue background no longer offers an advantage for detection of the target colors presented against it. An analysis of variance (background color x subject) showed that there were no significant differences between the mean RTs, averaged across the target colors, with the different backgrounds.

Target color

Figure 8 shows the mean RTs for each target color against each background. There were no significant differences in the RTs to the various colored targets against the black, green, and blue backgrounds. Against the yellow background, the mean RTs to the targets were significantly different ($F(5,35) = 9.82$, $p < .01$). It is apparent that this is due to the long RT to the orange target, whch was, of course, difficult to distinguish against the yellow background.

The same general pattern holds for these results as in Expt. I, although the differences between targets were not often significant. In general, the farther apart the target color was from the background on the color-wheel in Fig. 6, the longer the RT. On the yellow background blue and purple were the fastest colors, while orange was the slowest. Purple, red, and orange were the fastest on the green background. Against the blue background orange and red targets were the fastest. There was less variability between RTs to the targets against the black background, perhaps because all the targets had similar color and luminance contrasts. Removing these differences among the targets tended to equate their RTs.

Mean RTs and variability were much higher in Expt II than Expt. I. This was probably due to the fact that the subjects had no previous psychophysical experience. In addition, the experimental sessions were longer, and the subjects were perhaps becoming more fatigued.

DISCUSSION

Opponent color pairs generally yielded the shortest RTs. That is, the most detectable colors are those with the most color contrast with the background. The green target on the red background, the blue and purple on the yellow, and the red and purple on the green were either the best combination for that background or very close to it (see Figs. 5 and 8). The pattern of RTs follows the color-wheel rather nicely. This was generally true in both experiments. These results are consistent with Eastman's (7). He found that in the region of low luminance contrast, when color contrast becomes important, "targets with object and background farthest apart on the color circle will generally

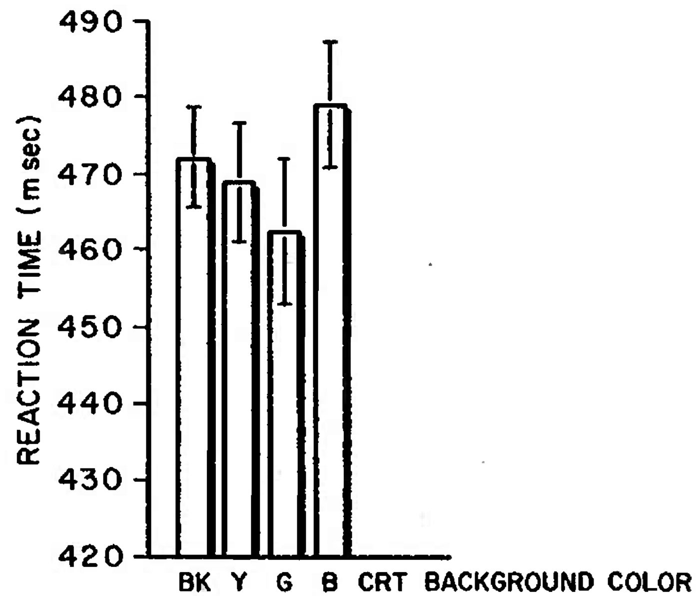

FIGURE 7. Mean reaction times for the four background colors in Expt. II, collapsed across target color. See Table I for abbreviations. (BK refers to the black background.) Error bars represent ± 1 s.e.m.

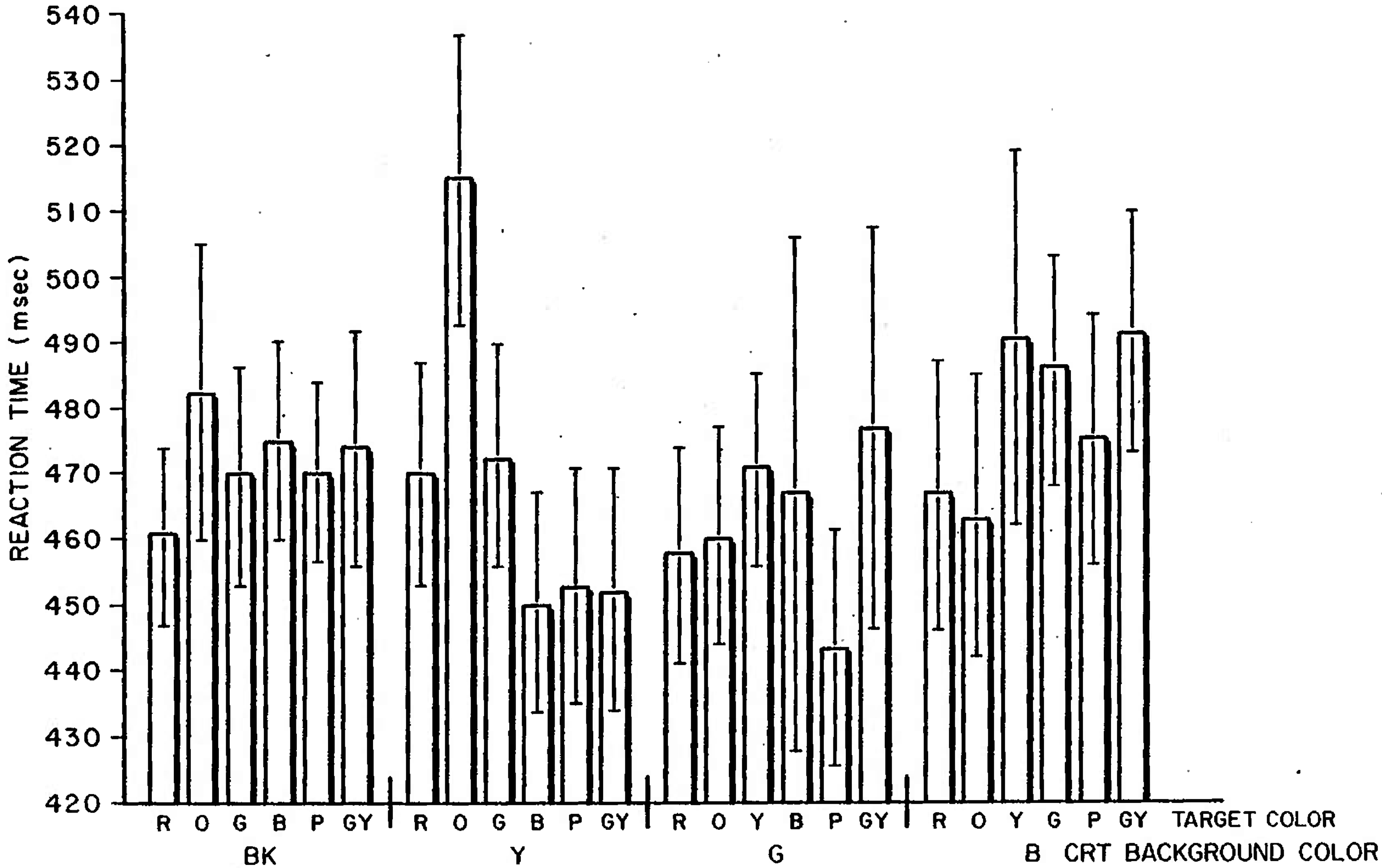

FIGURE 8. Mean reaction times for the various target colors on the four backgrounds in Expt. II. See Table I for abbreviations. Error bars represent ± 1 s.e.m.

have a higher visibility than those closer together" (p. 618).

Second, there was enhanced detection of several colored targets on the blue background in Expt. I. Recall that the blue color was substantially brighter under these viewing conditions than the other colors, which were approximately equal. Thus there was a substantial luminance contrast, in addition to a color contrast, between the blue background and the target colors. The only difference between the other background color/target color combinations was color contrast. It appears that this strong luminance difference can result in a significant increase in detectability. In Expt II when the luminance difference was eliminated, this advantage for the blue background disappeared. The lack of a similar enhancement with any of the other luminance-matched backgrounds for <u>all</u> target colors suggests that color contrast alone does not offer the same wide-ranging advantage.

The present results are in general agreement with those of Santucci et al. (8) who investigated visual acuity as a function of color and luminance contrasts. In one experiment they found that RTs to acuity targets of different colors were grouped most tightly for the blue and red backgrounds. In a second experiment investigating the effect of hue contrast, the blue background was clearly the best, implying something special about blue. Just as we found luminance contrast to be superior to color contrast for detection, they found luminance contrast to be superior for acuity. In fact, it was such a powerful effect that it masked their hue and saturation effects. In an investigation of the relative importance of color contrast and luminance contrast using brightly illuminated (100 fc) Munsell papers, Eastman (7) also found that, at high luminance contrasts, color contrast became relatively unimportant. This power of luminance contrast was demonstrated in the current experiment, as is evident in Figs. 4 & 5. Here, although there are differences in detectability between target colors on the red, yellow, and green backgrounds in Expt. I, these differences are masked by the effect of luminance contrast with the blue background. <u>All</u> RTs are reduced on the brighter blue, wiping out significant differences between target colors, as determined by the Newman-Keuls test, despite the significant overall <u>F</u>. Table II shows this lack of significant differences between targets on the blue compared to the large number of differences on other background colors. Santucci et al. summarized their studies by saying that "... all things being equal, the best visual acuity is obtained when there is a luminance contrast, whatever the hues may be" (p. 484). A similar conclusion most likely holds for detection as well. Thus it appears that, in the process of choosing colored backgounds against which one wishes to maximize the visibility of a colored target, luminance contrast should be made substantial. This should be done regardless of the particular colors chosen.

Given a substantial luminance contrast between background and target, does color contrast further enhance detectability? McLean (9) concluded that it is worthwhile to add color contrast to an existing luminance contrast in order to increase the legibility of a dial. The results of the present experiment, on the other hand, show that, with a large luminance contrast, further color contrast differences are substantially less important. However, since the range of intensities available on CRTs may not be large enough to provide the desired luminance contrasts, and since bright ambient lighting could wash out luminance contrasts, the presence of color contrast may indeed prove to be useful.

In view of the apparent importance of luminance contrast relative to color contrast, the question arises as to why the mean RTs were not fastest with the black background in Expt. II. In fact, as Fig. 7 shows, there were no significant differences in mean RT to the various colors.

The answer appears to be that, first of all, the "black" background on a CRT is not black, but gray, and the difference in luminance contrast between the gray and the colored backgrounds was far less than a factor of 10, calculated according to the formula $(Lb - Ld)/Ld$, where Lb and Ld are the luminances of the brighter and darker colors, respectively. Moreover, with each of the colored backgrounds there was at least one opponent-colored target which was detected very quickly, whereas with the black background the RTs to all the target colors were of moderate magnitude and much less variable. Thus, for example, the mean RT with the black background was 472 ms, ranging only from 461 to 482 ms. With the yellow background, RT to orange was 515 ms while RTs to blue, purple, and gray were all about 452 ms.

Finally, the ambient illumination had no effect on the detection of colored targets on colored backgrounds. This should not be construed to mean that color of illumination is never an important factor in the choice of CRT display colors. Illumination color probably had no effect in this study because it was very dim (.2 fc) compared to the CRT luminance of 4 fL. We would expect the ambient illumination to affect CRT color if they were the same intensity or if the CRT were dimmer. This interaction could cause problems if identification or careful discrimination of color is important (unlike the task in the present experiment) because strong ambient illumination can change the chromaticity of colors on a CRT screen by exciting the phosphors (10). Of course, one way to avoid problematic CRT/illuminant color interactions is to use subdued white light. Previous work has found evidence that this type of lighting may also enhance sonar detection performance (11,12).

CONCLUSIONS

Opponent color pairs are most quickly detected in a CRT display. Both luminance and color contrast are desirable, but a large luminance contrast between a colored background and small colored targets appears to be of most importance in enhancing detection. Maximizing color contrast should further enhance visibility, particularly when luminance contrast is reduced by limitations of the CRT or bright ambient illumination, but only to a relatively small extent. With the low ambient light level and moderately bright CRT luminance used in this experiment, color of room lighting had no effect on detection performance. Nevertheless, it is recommended that a subdued broad-band white light be used to preclude any interactions otherwise possible between CRT colors and colored ambient lighting.

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The detectability of seven colors presented on a CRT against four background colors was measured under four conditions of ambient lighting. Opponent color pairs were most quickly detected. Detection was enhanced by maximizing both luminance and color contrast, but luminance contrast was much more effective. Chromatic ambient lighting which was a log unit dimmer than the target luminance had no effect on performance.